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Procedia Computer Science 232 (2024) 337–347

Procedia Computer Science

www.elsevier.com/locate/procedia

5th International Conference on Industry 4.0 and Smart Manufacturing

Towards the Adoption of Industry 4.0 Technologies in the Digitalization of Manufacturing Supply Chain

Oluseyi Afolabi Adeyemi[a]* Pedro M. G. Pinto[b], Funlade Sunmola[c], Abiodun Musa Aibinu[d], Julius .O. Okesola[e], Esther .O. Adeyemi[f].

[a,b,c]*School of Physics, Engineering and Computer Sciences, University of Hertfordshire, Hatfield. AL10 9AB, United Kingdom.*
[d]*Summit University, Offa. 23402. Nigeria* [e]*Department of Computer Science, First Technical University, Ibadan. 23402. Nigeria* [f]*Department of Logistics and IT, MyBnK, London. EC2A 3DR, United Kingdom.*

Abstract

The study used multiple case studies to explore the findings from literature review on adoption of industry 4.0 technologies in manufacturing supply chains. It displays a digitalized supply chain as one of the best options for optimization of manufacturing companies processes and provides insights and some guidance on the industry 4.0 technologies for manufacturing companies to prioritize when starting the digitalization journey; to improve decision making, maximize efficiency and minimize costs. The main objective of the study is to explore various industry 4.0 technologies used in manufacturing supply chains and two propositions were suggested based on the three case companies investigated. The digitalization of manufacturing supply chains has an overall positive impact on how the supply chains operates and improves productivity and growth. It was concluded that industry 4.0 technologies are valuable tools from a managerial perspective, because they provide better process visibility and tracking of requisitions, improved efficiency, optimization of resources, easy to use templates, improved access to ordering data and reporting, improved decision making, and the supply chains are more autonomous.

Keywords: Supply Chains; Security; Manufacturing; Integration, Digitalization; Case Studies

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* Corresponding author. Tel.: +4411707 28 9388
E-mail address: o.adeyemi5@herts.ac.uk

10.1016/j.procs.2024.01.033

1. Introduction

A large portion of companies still relies on old methods and technologies because they have been foul proof for decades, when approached with the idea of new digital methods, understandably, they are reticent to make the change, when all that is seen is a substantial investment up front and a slow period of adaptation. The testimony of other pioneering companies that have leapt is crucial to serve as an example and pave the path for innovation. As such the choice to use a multiple case study method for this study was imminent. It is important to discuss and display the idea of implementing autonomous innovative technology in the manufacturing industry, since it may also cause drawbacks to employability rates and a shift in jobs in demand [39]. To encounter the problems and proffer solutions, a literature review is proposed. The proposed review is to support the objectives of this study, which are:

1. To review literature on emerging trends of industry 4.0 technologies
2. To explore different industry 4.0 technologies used in manufacturing supply chains.
3. To compare implementation practices to the degree of industry 4.0 technologies used in manufacturing supply chains.

The next section will focus on the literature review, then methodology of supply chains digitalization. A research questions was presented in Section 3. In Section 4, the detailed results are discussed. Lastly, the conclusion and future work are outlined in Section 5. Table 1a presents maturity and readiness models found in extant literature.

2. Literature Review

In this paper, key themes presented by digitalization and industry 4.0 technologies will be analysed for their backgrounds, their evolution, their utility and use cases towards supply chain management and the benefits and disadvantages that come with their implementation in business.

2.1. Background

Recent studies have focused on the idea of creating digital supply chains and moving towards a more automated and autonomous manufacturing industry. From product order generation or mass production to the manufacturing processes and the payment mechanisms, every stage of the supply chain can be digitalized for optimal efficiency and increased financial growth, post digitalization, when compared to the results pre digitalization. The main aim of a digital supply chain [DSC] structure is to remove human error from every part of the process and utilise machinery and software with capabilities that surpass those of humans to autonomously make the most beneficial decisions to the smart factory's efficiency and production costs. Some of the main innovative technologies that will integrate and make the DSC possible are Cloud Computing, Big Data and Analysis, Augmented Reality, Artificial Intelligence and Machine Learning, Autonomous Robots, Cyber-physical Systems, Internet of Things, Smart Contracts and Blockchain [2]. There are several types of industries: manufacturing, technology, finance, service, health care, including many others. Each type has its own set of challenges and unique characteristics. Most other industries' path towards digitalization is relatively straightforward and rapidly progressing, the manufacturing industry has a more complex structure and more human presence, making adaption harder to plan for and thus considerably lengthier. Other studies have mainly focused on the digitalization process, taking future perspectives into consideration for supply chains in general [2][21]. However, few studies have a focus solely on manufacturing companies' supply chains. [49] presented insights into several companies' move towards implementing industry 4.0 technology in their supply chain, taking managerial perspectives into consideration. According to Moore's Law and described by Prisecaru [34], the processing capability of core processing units doubles roughly every twelve to eighteen [12-18] months. If taken into consideration as a catalyst for the digitalization path due to its connection between people and machines, and data in real time, then a future where fully digitalized supply chains in most industries are standard is close.

2.2. Internet of Things [IOT]

The first theme that arises when exploring the concept of smart supply chains is Internet of Things and the interconnectivity amongst every stage of the supply chain. The IOT would be the base for the whole smart chain since it is what allows all the different machineries, robots and overall hardware that comprise the supply chain to connect to the same network and ultimately autonomously coordinate tasks amongst each other [27]. It is the connection between the physical and the web realms of any industry, product, object, or “Thing” [5]. There are a variety of interpretations for internet of things [14], it is an infrastructure connected to connected objects and allowing them to be managed, mined, and accessed, this means that there is an increase in speed of diagnoses with any halts to production and almost immediate problem-solving response by either another smart system or a report to anyone in charge of set stage. [16] define internet of things as being a wide range of smart objects [SOs] as extensions from actual physical objects so that they have capabilities of networking, processing, storing data and actuating upon certain protocols. A certain amount of situational awareness would be derived from all these capabilities, even if there was no artificial intelligence technology applied to the smart objects. The biggest risk to the growth and implementation of internet of things systems is cybersecurity, because without it any hacker can take advantage from security gaps in the network or any weakness within the smart objects and disrupt the data, which would have significative impacts not only within that SO’s network but also at a global network level. Additionally, the lack of scalability, integrity and interoperability of existing devices makes traditional security protocols and mechanisms insufficient against more modern threats [27]. Consequently, cybersecurity is currently one of the main barriers to the digitalization of supply chain unless the new standards for security are met.

2.3. Big Data and Analysis

When analysing the concept of a fully digitalized supply chain, the extensive amounts of data, resultant from all the digital systems gathering and storing new information every second across the chain’s entire network. These data sets can’t just be deleted, they are crucial as an instrument to improve the supply chain’s performance since it is becoming increasingly data dependent [28][36]. Data helps improve process level and firm level performance, by enabling a comparative for business analytics, thus offering better decision-making plans for the supply chain system [7]. The most prominent technology in the realm of big data and analysis is Highly Archived Distributed Object-Oriented Programming [Hadoop], using a collection of distributed devices and a dedicated computer programming model. Hadoop is an open-source framework that enables the distributed processing of immense volumes of data [41]. Hadoop has a framework that encompasses a series of HDFS and MapReduce compatible packages and tools, enabling the extension of its applicability to the many demands for coordination, analysis, performance management, and workflow design that appear frequently in big data applications [19]. There are a few challenges that come with trying to make full use of all the extensive amounts of available data. [50] summarized the challenges as 5V that is, volume, velocity, variety, verification, and value according to the typical supply chain management framework.

2.4. Cloud Computing

Supply chains need to maintain networking, software, analytics, and intelligence capabilities. The big data resultant from the supply chain operations needs to be stored, processed and readily accessible. However, manufacturing companies must attend to software issues and avoid adding possible hardware issues to the workload, by storing information in large servers on site, that require substantial maintenance [38]. The solution to that problem is cloud computing, a compilation of computing services delivered over the internet, which allows for faster access to resources, flexible supply chain management and economies of scale. [5] see the cloud as a capability to create an abstraction between the computing resource and its system design, enabling network access to a shared pool of configurable resources that can be immediately launched with minimal management or service provider interaction. Identifying on-demand self-service, broad network access, resource pooling, rapid elasticity, and measured services as the five essential cloud characteristics.

[40] identified three different types of service models used in cloud computing technology: Infrastructure as a service [IaaS], as a form of hosting. Platform as a Service [PaaS], as a standard set of programming databases as a basis upon which applications can be constructed and, Software as a Service [SaaS], as another form of hosting service, but with no hardware involvement. Some of the main benefits of the implementation of cloud technologies in supply chain are lower financial implications of IT services, flexibility of the service and automatic scale up with the growth of the supply chain. On-demand information is much faster than previous traditional methods and a better managerial perspective over resources. The drawback being cybersecurity as previously mentioned, because all the services operate on the internet.

2.5. Artificial Intelligence and Machine Learning

There is a human factor across most industries and supply chain departments. Systems have been reliant on people to operate for years, though nowadays there are new innovative technologies such as artificial intelligence [AI] and machine learning that can aid or even substitute and improve their process efficiency and quality. Artificial intelligence is based around the premise of a computer or machine that can replicate human intelligence and its analytical qualities and thinking structure through large amount of data input in conjunction with machine learning, continuously self-improving and upgrading with very little, if any human input or supervision at exponential rates. Since it is a computer system, it doesn't have any of the limitations of a normal human [32]. That is the most appealing insight for its applications to supply chain and any industry or sector in general. When using AI, problems are solved more quickly, more accurately, and managing much more data [46]. Artificial Intelligence has implemented in its processing system different types of mechanisms to mimic human intelligence, the main one being Machine Learning. There are four different types of A.I., reactive systems, limited memory systems, theory of mind systems and self- aware systems [37]. There are three major AI tools in supply chain management, each with different application areas in SCM. Agent based systems, can be applied to planning, and forecasting demand, customer relationship management, negotiation, and order picking. Following their generic algorithms, which apply to network design. Finally, expert systems can be introduced in inventory planning, make-or-buy decision, and supplier selection [29]. A fully developed artificial intelligent ecosystem that allows for seamless interaction between humans and machines would be of great benefit to supply chain management and the manufacturing industry as whole [18]. Because it would enable a whole new range of efficacy across all production processes and reduce costs by substituting employees who receive a wage, with machines that can work 24 hours a day.

2.6. Cyber-Physical Systems

Cyber physical systems are a class of objects or devices that have an integration of physical and computational capabilities which facilitate their interaction and cooperation with humans [17]. By adding a digital feature to these objects, it allows for new and improved ways to manage the supply chain. Since every object that acts in any process of the supply chain is connected to the same network, it gives live visibility of every action, therefore enabling an immediate and more accurate response to it from a managerial perspective [23].

According to Tonelli et al. [45], the principal characteristics of cyber-physical systems includes integration, heterogeneity, interoperability, decentralization, autonomy, interconnection, and modularity. The implementation of cyber-physical systems across the supply chain would solve many long-lasting problems, due to their multi purposeful nature and scalability. The main solutions found were, the enhancement of machinery uptime, since the machines would have more analytical capabilities, self-maintenance, and problem reporting capabilities. Process coordination amongst machines, through networking. Reduction of machinery and equipment power consumption because more efficient machines produce more, while consuming the same power, therefore from a rational point of view, these machines consume less. Efficiency management within tool management, simplification of informational processes. Continuous quality control along production process, because all the devices that are part of that process have now the capability of analysing, reporting, and sustaining the product [26]. Amongst many other solutions to problems that otherwise would not be solved without the push for a more digital supply chain.

2.7. Industrial Robots

In the manufacturing supply chain, there is a need to always innovate and turn the processes more efficient while also reducing costs. Industrial robots were created to substitute or aid human workers in the manufacturing processes, logistics and even analytical processes. Industrial robots are machines specifically programmed to perform a task or set of tasks repeatedly with high accuracy and excellent technical precision. According to Buerkle et al., [8] Industrial robots have different characteristic applications such as warehouse and transport, assembly and light machining, quality inspection, and, packing and palettization. Within the realm of packing robots there is a cooperation with other devices and smart objects to make sure that the right product is being packaged. This is mostly achieved with the help of programmable logic controllers and photoelectric sensors. Overall, robots and human workers both have benefits and disadvantages as presented in Table 1. For most businesses it is an easy choice, though a comparative analysis of both is more revealing.

Table 1 - Comparison between human factor and robot factor [Source: Barosz et al., 2020]

	Human Factor	**Robot Factor**
Work Parameter	Unstable, slow work, fatigue	Stable, fast work
Adaptation for new task	Fast adaptation	Slow programming
Flexibility, working area	Large flexibility, large operating range	Lower flexibility, limited range
Errors and failures	High human errors rate	Low failure rate
Replacement and repair	Can be replaced	Require repairing
Labor Cost	High	Low
Investment cost for human/robot workstation	Low	High

2.8 Blockchain and Smart Contracts

Finance is a key element when analysing the supply chain of any company. Supply chain finance (SCF) is mostly a subset of supply chain management; however, it is increasingly becoming more crucial for companies due to the current economic state. Companies need to maintain their assets, facilitate product payment, and automate product orders, stay liquid and maintain cash flow. Blockchain technology's decentralized, unique, verified operational framework makes it stand out as a solution to SCF. Blockchain is a collection of records and information linked with and verified by each other, which makes them very strongly resistant to alteration, because it is protected by cryptography [30]. In the context of supply chain management and product quality control, blockchain can be used to verify within the supply chain, what part of the process has caused fault in the product, so that the problem can be resolved quickly [44]. Smart contracts are another concept being explored in the realm of supply chain finance; these are electronic transfer protocols that ensure that all legal terms of any transaction are respected. By digitally enforcing negotiation and execution of the transaction terms, with an underlying legal contract embedded in the transaction itself, the contract replaces any third parties previously required for transactions and assures mutual fulfilment of common contractual conditions and legal obligations before any monetary quantity is allocated [33]. Another benefit that emanates from smart contracts besides cost reduction, is the ability to operate globally with no limits, thus driving scalability to exponential rates that otherwise cannot be achieved in the current financial model. Abeyratne and Monfared [1] identified the key technological advantages of blockchain technology for supply chain applications such as durability, transparency, immutability, and process integrity. Table 1a presents the maturity and readiness models found in extant literature according to [31].

Table 1a: Maturity and readiness models found in the literature [Source: Pacchini et al., 2019]

Maturity and Readiness Models	Authors
ACATECH Maturity Index	Schuh et al.
The Singapore Smart Industry Readiness Index	Basll and Doucek
IMPULS - Industrie 4.0 Readiness	Lichtblau et al.
DREAMY - Digital Readiness Assessment Maturity Approach	Mittal et al.
A maturity approach for assessing Industry 4.0 readiness and maturity of manufacturing enterprises.	Schumacher et al.
SIMMI 4.0 – A Maturity Approach for Classifying the Enterprise-wide IT and Software Landscape Focusing on Industry 4.0	Leyh et al.
Industry 4.0: Building the digital enterprise.	Sarvari et al.
Concept for an evolutionary maturity based Industrie 4.0 migration approach	Stefan et al.
Three stage maturity model in SMEs towards Industry 4.0	Ganzarain and Errasti

3. Methodology

A two-stage research methodology was used for this study. First, a literature review. A collaborative approach is adopted in this study aimed on summarizing existing literature to recognize patterns in respect to previous publications. The literature review steps include articles collection, exclusion analysis, descriptive analysis, dimension and category selection, and evaluation. In this study, the databases used to select relevant articles was ProQuest with 13 databases and Google Scholar. A focused search phrase is used: Adoption of Industry 4.0 Technologies AND [Manufacturing AND 'Supply Chain'] in title, Abstract or author specified Keywords. The initial search identified 108 publications. Initial filtering was to select eligible articles. Following the initial filtering of articles 55 papers were identified. Only papers written in English language were included. The second stage of evaluation was to read abstracts and those whose focus is not on Industry 4.0 technologies adoption in supply chain were excluded. Following this

step, 45 papers remained. The final selection remained through reading the full text of the papers for further filtering and inclusion. This resulted in final selection of eligible and credible 45 papers.
The second stage of the study is exploratory and for furthering understanding of concepts which have not been deeply investigated [15][47][48]. Hence, the second stage methodology for this study is qualitative and multiple case studies methods are used, accompanied by the initial literature review. The data selection criteria include adequate level of manufacturing activity, adoption of industry 4.0 technologies, case companies' diversification and triage of different product manufacturers to provide insights to the research question (RQ) of:
How does implementation practices influence the degree of application of industry 4.0 technologies in manufacturing supply chains?
Secondary data were used gathered from annual reviews, case companies' documents and websites, public company data, company magazines, newsletters and presentation materials to customers and stakeholders. The data set includes information on how the case companies' supply chain operates, the present and future projects in process digitalization, inherent benefits, and disadvantages of the digitalization of their supply chain, financial implications, and outcomes. The methods of implementation were used for a more seamless adaptation period, thus giving better managerial insights. The collected data were triangulated from various sources, literal replication was conducted on the three case companies to spot similarities of concepts and the validity was ensured based on the confrontation of case companies' data with established constructs from the literature.

4. Discussion and Results

The three selected companies are analyzed based on their adoption of industry 4.0 technologies in relation to their supply chains and contributions towards digitalization. The discussion tabulates how each of the technologies contribute to the efficiency of the supply chains and the benefits of using the methods from a managerial perspective. Examples of industry 4.0 technologies common to the chosen case companies includes Industrial robots, IOT systems and Cloud computing. The discussion extends to the exploration of specific innovative technologies that make each of the case companies' supply chains unique, based on their operational requirements.

4.1. Case Overview

Table 1b - Case Overview

ID	Type of Organization	Size (no. of employees)	Main Business	Approach	I4.0 Technologies Used
C1	Manufacturing Company	600,000 +	Automobile manufacturing	Strategy, Goals and KPI's	Autonomous Industrial Robots, Big Data and Cloud Computing, Networks and Internet of Things, Interconnected Smart Chains, Simulation and Big Data
C2	Manufacturing Company	1,300 +	Juice manufacturing (FMCG)	Project	Industrial Networks and Cloud Computing, Industrial Robots, Augmented Reality, Big Data, and Internet of Things
C3	Manufacturing Company	13,500 +	Coffee capsules manufacturing and Coffee machine distribution	Goals and KPI's	Machine Learning and Internet of Things, Artificial Intelligence, Additive Manufacturing, Cyber-physical Systems

Table 1b gives an overview of the case companies in terms of its manufacturing activities, size of the organization, the main business of the company, and its strategic approach to the adoption of industry 4.0 technologies. The case selection criteria include the specific industry 4.0 technologies used in each company for digitalizing the supply chains and the maturity of each company in its digitalization journey.

4.2. Case Company 1 (C1) Industry 4.0 Technologies

The secondary data shows investments made by case company 1 in terms of the adoption of industry 4.0 technologies used in digitalizing its supply chain as presented in Table 2. A logistic drone which is used in the logistics department to improve the warehouse integrity operation will be considered among other industry 4.0 technologies used in case company 1. Previous activities carried out by an operator using a lift platform to visually compare the volumes' references to the storage list by location; now uses a drone to do the inventory check. With the task being increasingly automated without the use of industrial equipment and with little to no human interaction, it is possible to optimise data consumption and service efficiency while posing minimal risk to workers and preventing manual errors, this is in line with the findings of [7]. The logistic drones increase operations productivity, ensure process stability, and pave the way for digitalization like the autonomous industrial robot, that confirms the work done by [8]. To test the integrity of warehouses and make sure that what is intended to be stored matches reality. No safety precautions need to be taken that would otherwise be done if a human worker were to execute the job, this procedure is time efficient.

Table 2 – Linking case company 1 [C1] technology use with industry 4.0 technologies.

Case Company's Technology Use	Industry 4.0 Technology
Logistics drone	Autonomous industrial robots
Industrial machines network	Big data and Cloud computing
Predictive maintenance	Networks and Internet of things
Prioritization & vehicle location	Interconnected smart chains
Road test predictor	Simulation
E-paper	Internet of things and big data

4.3. Case Company 2 [C2] Industry 4.0 Technologies

The Manufacturing Execution System [MES] is discussed among other industry 4.0 technologies used in case company 2. MES is a software programme created to optimise and simplify the manufacturing plant's production process. Manufacturing and/or operations managers use this information to make informed decisions about production schedules, quality assurance, and inventory management because it gives real-time information on the production process. That is also verified by [9]. MES collects data from a variety of sources, including tools, sensors, and workers, at the factory floor level [4]. The data are analysed to provide insightful information as stated by [7]. Additionally, MES automates a few processes, including data gathering, quality assurance and scheduling, which lessens the workload of human workers and lowers the possibility of mistakes. MES purposes throughout the supply chain are not limited to production control, quality control, inventory management and maintenance management. Moreover, it ensures that inventory levels are adjusted to reduce waste and boost productivity and to satisfy output demands in line with the work of [28][36]. MES typically oversees the maintenance of machines and equipment by planning preventive maintenance tasks, monitoring the progress of maintenance operations, and identifying any equipment or machinery malfunctions and raising warnings as required as revealed in the study by [8]. Table 3 highlights some of the industry 4.0 technologies used in case company 2.

Table 3 – Linking case company 2 [C2] technology use with industry 4.0 technologies.

Case Company's Technology Use	Industry 4.0 Technology
5G Network	Industrial Networks and Cloud Computing
Smart Warehouse	Industrial Robots
AR Maintenance	Augmented Reality
Manufacturing Execution System [MES]	Big Data and Internet of Things

4.4. Case Company 3 [C3] Industry 4.0 Technologies

For case company 3, the digital twin [DT] technology is discussed as a representation of other industry 4.0 technologies that are adopted in its manufacturing supply chain. DT is creating a digital version of a physical object to test its usage, find flaws, make improvements and overall efficiency of its usage. The company creates a digital twin of its machines, which is used to run all types of tests, to determine the theoretical operational limits of each machine, to predict which parts of the machine is likely to fail. From that information, timely predictive maintenance can be planned in an efficient manner to prevent machine parts failure, because digital twin gives a very accurate insight on how the machine behaves and what needs to be done, in the appropriate order according to insights from [23]. DT enables higher level of interaction between the customer and the product, a possibility for customization and a way for the customer to understand how the product meets their needs and gives the options to choose, from available information. That leads to improvements in customer satisfaction and lower product return and refund rates. By creating a digital model of the manufacturing operations, systems, and the factory's supply chains, predictions on reducing production down time and predictive maintenance can be made based on theoretical models and that confirms the findings of [26]. Table 4 presents the industry 4.0 technologies used in case company 3.

Table 4 – Linking case company 3 [C3] technology use with industry 4.0 technologies.

Case Company's Technology Use	**Industry 4.0 Technology**
Smart Coffee Machines	Machine Learning and Internet of Things
Client Maintenance Platform	Artificial Intelligence
3D Printing	Additive Manufacturing
Digital Twins	Cyber-physical Systems

4.5. Overview of Implementation Practices

Table 5 - Implementation Practices

Challenges	Practices	Level of Implementation		
		Low	Medium	High
Implementation Strategy	Define a strategy for implementation of new technologies		C3, C2	C1
	Implement different technologies based on strategic approach	C2	C1, C3	
	Accurate financial resource allocation		C1	C3, C2
	Plan every technological use		C2, C3	C1
	Outsourcing new technologies	C3		C1, C2
Understanding of the Technology	Measure risks of a highly digitalized supply chain	C3	C2	C1
	Use experts in the field to assure maximal efficiency and safety of usage	C3		C2, C1
	Look into core values of previously introduced technology before investing in new models		C1	C2, C3
	Prioritize investments without negatively impacting non-industry 4.0 structure		C3	C1, C2
Exploration of Digitalization Scalability	Explore each technology through initial small-scale implementation		C2, C3	C1
	Have a "step by step" methodical approach while implementing new technology		C3	C1, C2
	Keep exploring opportunities to expand			C1, C2, C3
	Establish ways to maintain control over newly implemented processes	C3	C2	C1
Employee Adaptation Strategy	Build a strong company culture of digital skills	C2, C3		C1
	Lead initiatives and serve as example towards welcoming digitalization	C2	C1, C3	
	Invest significantly on employee capacity of understanding how new technologies operate		C2, C3	C1
	Invest in employee training and support			C1, C2, C3

Considering the three case companies and the implementation practices from Table 5, some propositions are generated in relation to the level of implementation of the industry 4.0 technologies adopted in their manufacturing supply chains namely.

Proposition 1: Continuous exploration of opportunities to expand digitalization scales has a positive direct *relationship to a high level of utilization of industry 4.0 technologies in the three case companies.*

Proposition 2: Investment in employee training and support towards adaptation strategy has a direct influence on a high level of utilization of industry 4.0 technologies in the three case companies.

4.6. Cross comparison of industry 4.0 technologies adopted in the three case companies.

Close observation of Table 6 suggests that *big data, cloud computing and industrial robots* are the industry 4.0 technologies well adopted by the three manufacturing companies' supply chain in this study. Hence, it is a digitalization trajectory guide for manufacturing and/or operations managers to prioritize these three industry 4.0 technologies as they embark on supply chains digitalization project before investing in other specific technologies based on their unique operations.

Table 6 - Comparison of industry 4.0 technologies in use across the three case companies

Industry 4.0 Technology	Case company 1 [C1]	Case company 2 [C2]	Case company 3 [C3]
Big Data	x	x	x
Cloud Computing	x	x	x
Artificial Intelligence and machine Learning	x		x
Cyber-physical Systems	x		x
Industrial Robots	x	x	x
Blockchain	x		
Simulation	x		x
Augmented Reality		x	
Additive Manufacturing	x		x

5. Conclusion

Based on a qualitative analyses of the industry 4.0 technologies used at each case company and for the implementation to have happened seamlessly, leadership commitment of each case company to transform the supply chain and definition of a clear path for innovation are important from a managerial perspective. The results indicate that continuous exploration of opportunities to expand digitalization scales and investments in employee training and support are of major relevance in digitalizing manufacturing supply chains. Close examination of the three case companies established financial growth and a new level of maturity in their supply chain with the implementation of the industry 4.0 technologies. Notwithstanding the significant disparity in the case companies' sizes, the use of industry 4.0 technologies such as *big data, cloud computing and industrial robots* are suggested for adoption when starting the supply chains digitalization project for manufacturing companies. Hence, providing a guide for manufacturing and/or operations managers. This study illustrates that digitalizing the supply chain is a benefit to manufacturing companies and the efficiency boost, cost reductions, improved decision making and return over investments are significant. However, there are still several important areas to be explored in future studies such as, the role of human factors/actors in the adaptation of the novel digital manufacturing supply chains. Another study could focus on the view of employees' resistance or employee's substitution due to the implementation of industry 4.0 technologies in the manufacturing supply chain. Finally, to generalize the findings of this study, more companies' data with comparable sizes across different markets, industries, sectors, and organizational contexts would be required.

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